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Plasma volume during heat stress and exercise in women

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To determine whether PV was affected by the menstrual cycle, we studied five women during exercise and passive heating. The exercise bout (80% $\dot{V}O_2$ peak) on a modified cycle ergometer and the passive heat stress were done in a hot environment ~~(T_a=50°C, P_w=1.61kPa)~~ during the follicular and luteal phase. Esophageal temperature (T_{es}) was measured continuously. $\dot{V}O_2$ was measured immediately after each blood sample, which was drawn after each 0.2°C increase in T_{es}. Initial PV was estimated at rest during the follicular phase. PV changes from rest were calculated at each T_{es} from Hb and Hct. During passive heating, PV decreased by a mean volume of 156 (±80) ml to 2.83 (±0.09) ℓ in the follicular phase. During the luteal phase, there was a larger volume reduction (300±100ml) during passive heating, and the final PV was lower (2.47 ± 0.18 ℓ) than in the follicular phase. During exercise, PV decreased 463 (±90) ml to 2.50 ± 0.11 ℓ in the follicular and 381(±70) ml to 2.50 (±0.23) ℓ in the luteal phase. These data indicate that there is a menstrual cycle effect on PV during passive heating such that final PV is lower during the luteal phase.
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During severe exercise there is a greater PV loss during the follicular phase, yet the final PV is not different between phases. Keywords:

Summary

To determine whether PV was affected by the menstrual cycle, we studied five women during exercise and passive heating. The exercise bout (80% $\dot{V}O_2$ peak) on a modified cycle ergometer and the passive heat stress were done in a hot environment (T_a = 50°C, P_w = 1.61 kPa) during the follicular and luteal phase. Esophageal temperature (T_{es}) was measured continously. $\dot{V}O_2$ was measured immediately after each blood sample, which was drawn after each 0.2°C increase in T_{es}. Initial PV was estimated at rest during the follicular phase. PV changes from rest were calculated at each T_{es} from Hb and Hct. During passive heating, PV decreased by a mean volume of 156 (± 80)ml to 2.83 (± 0.09)ℓ in the follicular phase. During the luteal phase, there was a larger volume reduction (300 ± 100ml) during passive heating, and the final PV was lower (2.47 ± 0.18ℓ) than in the follicular phase. During exercise, PV decreased 463 (±90) ml to 2.50 ± 0.11ℓ in the follicular and 381(± 70) ml to 2.50 (± 0.23)ℓ in the luteal phase. These data indicate that there is a menstrual cycle effect on PV during passive heating such that final PV is lower during the luteal phase. During severe exercise there is a greater PV loss during the follicular phase, yet the final PV is not different between phases.

Key Words: Severe exercise, Menstrual cycle, Follicular phase, Luteal phase

There are conflicting descriptions of the plasma volume response to heat stress and exercise in women, even when the phase of the menstrual cycle has been controlled (6,9,10,21,27,28). Wells and Horvath (27) reported that women hemodiluted while resting in a hot environment (48°C, 10% relative humidity), and this response was unaffected by phase of the menstrual cycle. In a study which had similar environmental conditions to that of Wells and Horvath, but longer duration of heat stress, Senay (21) observed a hemoconcentration during both the pre-ovulatory and post-ovulatory phases of the menstrual cycle.

During moderate exercise in a hot environment (48°C, 10% relative humidity), no hemoconcentration was observed (28) during the follicular, pre-ovulatory and luteal phases of the menstrual cycle. In a later report from the same laboratory (6), both heat acclimated and non-acclimated women hemoconcentrated after walking in a hot environment. Others have verified that hemoconcentration occurred during cycle ergometer exercise in a hot environment (9,10,23), although there are conflicting reports of whether the phase of the menstrual cycle affects the degree of hemoconcentration. Fortney and Senay (9) reported no menstrual cycle effects on the hemoconcentration during exercise. Gaebelein and Senay (10) suggested that hemoconcentration occurred less rapidly in the luteal phase than in the follicular phase during moderate exercise. Previously (23), we observed a similar degree of hemoconcentration based on pre- and post-exercise blood samples after women exercised in a moderately hot environment in both the follicular and luteal phase, but noted that absolute plasma volume based on pre- and post-exercise blood samples after exercise was less during the luteal phase, which reflected the lower initial plasma volume during the luteal phase.

Recently, there have been a number of preliminary reports describing plasma volume fluctuations during the menstrual cycle (23,25,30). All three

laboratories reported lower plasma volume at rest during the mid-luteal phase, than during the mid-follicular phase. Although there have been many investigations studying the menstrual cycle effects on plasma volume loss during exercise or heat stress (6,9,10,21,23,27,28), almost all (6,9,23,27,28) have measured indices of plasma volume before and after the stress, rather than during the stress, when the fluid exchange occurs.

The primary purpose of this study was to examine how the menstrual cycle affected the dynamic plasma volume loss resulting from both exercise and passive heat stress. Therefore, blood samples were drawn periodically throughout the time of exercise or heat stress. A secondary intent of this study was to determine whether hemoconcentration occurred in women subjected to a passive heat stress after previous equilibration in a subjectively determined "thermoneutral" environment.

Methods

Five healthy women (Table 1), who were not using oral contraceptive agents, volunteered to serve as subjects for the protocol, which was previously approved by an institutional review board. Each reported having a normal menstrual cycle as defined by regular periodicity, and verified by a normal luteal elevation in basal body temperature. All subjects were familiarized to the experimental techniques prior to the study.

Four experiments were conducted during the winter on each subject. Two experiments were conducted in which the subject was passively heated (T_g = 50.4°C, P_w = 1.61 kPa), one during the follicular phase (days 4-6) and one during the luteal phase (days 19-22) of the menstrual cycle. In the other two experiments, the subjects exercised at approximately 80% of the $\dot{V}O_2$ peak during both the follicular and luteal phase in the same environment as described above. All experiments were in the morning, although the passive heating

experiments averaged three hours (178 min) long, while the exercise was approximately 9 min. The subjects did not eat or consume caffeine for at least 8 h prior to the experiments, and were normally hydrated.

The subjects were dressed in shorts, singlet, socks and shoes during the experiments. A separate room from the environmental chamber was used for equilibration and instrumentation. The ambient temperature of this room was adjusted so that each subject felt comfortable, and averaged 28.8°C, P_w = 0.8 kPa. The subject placed a catheter containing a thermocouple in her esophagus at the level of the heart for the measurement of core temperature (T_{es}). She drank approximately 170 ml of water while swallowing the T_{es} thermocouple. She was weighed before sitting in a wheelchair. Skin thermocouples were attached at 8 sites for skin temperature measurement. Mean skin temperature ($\bar{T}_{sk}$) was calculated by area weighting of each regional skin temperature (11,19). A venous catheter was inserted into an arm vein. After 30 min of equilibration, a blood sample was drawn (16 ml).

The subject was then transported in the wheelchair to the environmental chamber. Resting T_{es} was measured before she entered the chamber. The subject was wheeled directly next to the chair of a modified cycle ergometer (3). She was instructed to closely maintain the seated position as she moved between the two chairs.

During the passive heating experiments, blood samples were drawn each time that T_{es} increased 0.2°C. The experiment was terminated after T_{es} had increased 0.8°C or the subject complained of heat syncope. The average time of the last blood sample taken from all subjects for the passive heating experiments was 116 (± 41) min during the follicular phase and 169 (± 66) min in the luteal phase.

During the exercise experiments, the subject began to cycle at approximately 80% $\dot{V}O_2$ peak within two minutes after entering the environmental chamber. Blood samples were drawn each time that T_{es} increased by 0.2°C (2.5 min intervals), until the T_{es} had increased by 0.8°C. The average time of the exercise experiment was 9 ($\pm$ 2) min, with no difference between phases.

Blood volume was estimated by the method of Allen et al (1) using the weight of the subject measured during the follicular phase in the passive heating experiment. Plasma volume (PV) was calculated from the estimated blood volume and hematocrit. In each blood sample, hemoglobin concentration (Hb) and hematocrit (Hct) were measured. Relative changes in plasma volume during the experiments were calculated from Hb and Hct (24). The pre-stress Hb and Hct were used to calculate the baseline plasma volume for the other three experiments. Hemoglobin was measured using a hemoglobinometer (Coulter Electronics). Plasma protein concentration (P_p) was measured by refractometry. Plasma sodium (Na^+) and potassium (K^+) concentrations were measured by ion-selective analysis (Nova Biomedical) and total circulating protein (TCP) was calculated from changes in P_p and PV.

Linear regression equations were calculated to describe the plasma volume loss over time for each experiment. The slopes of the regression equations were compared by a two-way analysis of variance across menstrual cycle phase and method of heating. A one-way analysis of variance (16) with repeated measures was used to compare resting PV and TCP during the follicular and luteal phases. A three-way analysis of variance (T_{es} x menstrual cycle phase x time) with repeated measures was used to compare PV, P_p, TCP and Osm (16). Tukey's test of critical difference was used where appropriate. All differences are reported at $p < 0.05$, unless otherwise noted.

Results

Table 1 shows the individual characteristics of the subjects. The normal increase in core temperature (T_{es}) at rest during the luteal phase was observed and averaged 37.25 ± 0.23°C, while T_{es} averaged 36.97 ± 0.21°C in the follicular phase (Table 2).

None of the subjects was able to remain in the hot environment long enough for the T_{es} to increase 0.8°C during the luteal phase, even though the exposure time was 46% longer in the luteal than in the follicular phase. However, a final blood sample was drawn from two subjects after the core temperature increased approximately 0.7°C. The other three subjects were unable to complete the experiment during the luteal phase. During the follicular phase, the T_{es} increased 0.8°C in only three subjects, although the last blood sample was drawn on a fourth subject when her T_{es} had increased approximately 0.7°C.

Mean resting plasma volume (Table 3) was lower during the luteal phase (2.83 ± 0.22 ℓ) than the follicular phase (2.97 ± 0.13 ℓ). Plasma volume decreased and plasma Na^+ concentration increased with time of exposure to either stress (Fig. 1 and 2, Table 3 and 4). Plasma K^+ concentration increased during exercise (Table 4) but did not change significantly during the passive heating (Table 3). The passive heating stress resulted in a lower final PV during the luteal phase (2.47 ± 0.18 ℓ) than in the follicular phase (2.83 ± 0.09 ℓ). Plasma volume fell rapidly during the first few minutes of exercise in both phases (Fig. 3 and 4). Approximately 70% of the volume lost during exercise occurred by the first blood sample. Plasma volume was weakly correlated with TCP during exercise (r = 0.733). The final exercise plasma volume was not different between menstrual cycle phases. However, the absolute volume lost during exercise was 90 ml greater during the follicular phase. Although exercise

resulted in a more rapid loss in PV than during passive heating, the final PV (2.5 ℓ) was not different from exercise in the luteal phase. On the other hand, the final PV (2.83 ℓ) during passive heating in the follicular phase was clearly much higher than in the other three experiments (Table 3, Fig. 1).

The average time of the last blood sample taken from all subjects for the passive heating experiments was 116 (± 41) min during the follicular phase and 169 (± 66) min in the luteal phase.The average time of the exercise experiment was 9 (± 2) min, with no difference between the phases.

There were no differences in sweating rate (calculated from change in body weight) between menstrual cycle phases during passive heating and exercise. The mean sweating rate during passive heating was 7.4 (± 1.3) and 6.5 (± 1.2) $g \cdot min^{-1}$ in the follicular and luteal phase respectively. During exercise, sweating rate was 16.9 (± 3.6) and 17.2 (± 2.8) $g \cdot min^{-1}$ in the follicular and luteal phases respectively.

Discussion

These experiments were designed to investigate whether the menstrual cycle does affect plasma volume loss during an exercise or passive heating stress. From indirect evidence, we hypothesized that there would be differences during the menstrual cycle in the maintenance of PV during exercise or heat stress. First, resting PV fluctuates during the menstrual cycle (23,25,30) and the mechanism by which PV is regulated at these various volumes might also influence PV dynamics during stress. Secondly, there are differences between menstrual cycle phases in the fluid volume regulatory hormones (2,7,12,15,22). Specifically, aldosterone concentration (12,15) and plasma renin activity (15) are increased during the luteal phase, and plasma vasopression concentration has been reported to fluctuate throughout the menstrual cycle (7), although others (22) have failed to detect significant differences in plasma vasopressin. The

luteal elevation in plasma aldosterone concentration and plasma renin activity persists during exercise (unpublished observations) and might influence plasma volume dynamics. Furthermore, both basal plasma osmolality and the plasma osmolality at the onset of thirst is lower in luteal phase of the menstrual cycle (2,22). There is also a decreased osmotic threshold for release of vasopressin and a lower sensitivity of the plasma vasopressin (pAVP) : plasma osmolality (pOsm) relationship during the luteal phase (2,22). The change in the sensitivity of the pAVP : pOsm relationship during the luteal phase could also change fluid volume dynamics during exercise.

Resting plasma volume was larger during the mid-follicular phase than in the mid-luteal phase (Figs. 1 and 2, Tables 3 and 4). A lower basal plasma osmolality has been reported during the luteal phase (2,22) however, the subtle changes in the osmoregulation of vasopressin during the luteal phase may not be adequate to explain the lower plasma volume that was observed in this study. We have observed previously (unpublished observations) that both plasma aldosterone and plasma renin activity are elevated at rest (35°C) during the luteal phase, which may be a consequence of the lower plasma volume during the luteal phase. Increased plasma aldosterone (12,15) and plasma renin activity (15) during the luteal phase may be another part of the fluid volume homeostatic mechanism. Although plasma protein concentration was not different between the two phases in the present study, the total circulating protein in the plasma was significantly lower in the luteal phase (Tables 3 and 4) which is a further indication that the lower plasma volume during the luteal phase is the result of fluid volume homeostasis.

During passive heating, there are conflicting reports about blood volume responses in women. Senay (21) reported that females hemoconcentrated during a 10 hour exposure to a hot environment, while Wells and Horvath described a hemodilution after a shorter duration exposure to a similar environment (27).

It has been suggested recently (13) that postural effects may have confounded Wells and Horvath's interpretation of hemodilution during heat exposure in women (27). In the current investigation, the initial blood sample was drawn after the subject had equilibrated in a wheel chair at a comfortable ambient temperature. As described in METHODS, precautions were taken to minimize postural disturbances after the initial blood sample was drawn. Our observation that women hemoconcentrate during passive heating after equilibration in a subjectively determined "thermoneutral" room, lends credence to Harrison's suggestion (13) and confirms the work of Senay (21).

During these passive heating experiments the PV dynamics appear to be different between phases. Although initial PV was lower during the luteal phase, there was a more rapid decrease in PV per incremental change in T_{es} than occurred in the follicular phase (Fig. 1, Table 3). In other words, the normal increase in resting T_{es} during the luteal phase, (approximately 0.3°C) was associated with a greater PV loss during passive heating. The disproportionately large decrease in PV in the time that T_{es} increased from 37.6 to 37.8°C (Fig. 1) indicates that more fluid was lost from the vasculature during that time than during any previous 0.2°C increase in T_{es}. Increased sweating rate or respiratory water loss might explain the greater volume of plasma lost at that time since evaporative heat loss would be the only avenue of heat dissipation in this environment. Figure 2 demonstrates that this apparent difference in PV dynamics between phases is not seen when PV is presented as a function of time. Although the slopes of the individual PV : time relationships were not statistically different between menstrual cycle phases, there was a greater (1.65x) mean PV loss per unit time during the luteal phase. The final PV (0.6°C increase in T_{es}) during passive heating was lower in the luteal than in the follicular phase. However, the heat exposure lasted 53 min longer in order to

increase T_{es} 0.6°C in the luteal phase. Plasma volume may be maintained at a higher level during the follicular phase even if the time of heat exposure is similar. For example, Fig 2 shows that at the time of the last blood sample during the follicular phase, plasma volume is considerably greater than during the luteal phase. It must be assumed that the forces opposing the fluid exchange from the vasculature are consistent during passive heating. Thus, the same homeostatic mechanism which results in a lower plasma volume at rest during the luteal phase is also operating during passive heating. One contributing factor could be the lower sensitivity of pAVP : pOsm (2,22) during the luteal phase.

The lower absolute PV after passive heating may simply be a consequence of a greater degree of venous pooling. However, it is also possible that there are hormonal as well as temperature influences. Estradiol has been reported to block the release of NE at the neuron, preventing the catecholamine from reaching the α-adrenoreceptor in vascular tissue (26). The higher circulating estradiol after ovulation may be effectively attenuating the release of norepinephrine at the post-junctional receptors. Consequently, the vascular smooth muscle may be less contractile during the luteal phase which might explain the greater net filtration during passive heating and lower initial PV, as well as increased venous pooling.

The menstrual cycle effects on PV dynamics are somewhat different between exercise and passive heating. During exercise there is a rapid decrease in PV in women which is dynamically similar to men (8). PV declines slightly faster in the follicular phase (Figs. 3 and 4) but PV loss per unit time was not statistically different from the luteal phase. Gaebelein and Senay (10) reported a more rapid decrease in PV during low intensity cycle ergometer exercise in the

follicular phase. The high exercise intensity used in the current study may have obscured this effect on vascular dynamics which occurs during low intensity exercise. The much greater stress in this study would be expected to greatly elevate plasma catecholamines in comparison to moderate exercise (5). Higher concentrations of circulating catecholamines during severe exercise would be associated with a greater capillary filtration pressure and consequently increase the amount of fluid lost from the vascular compartment (29). The higher concentration of circulating catecholamines also could alter distribution of the blood volume such that perfusion of various organ beds, including the liver, gut, muscle and skin, would be different from that during moderate exercise (20). An explanation of the trend for more rapid hemoconcentration and the larger absolute volume lost during exercise during the follicular phase might be that there was a larger initial plasma volume. There is a relative hypovolemia during the luteal phase, and PV has been shown to decrease more rapidly in normovolemic men that in hypovolemic men (8), although the difference in PV between phases of the menstrual cycle (~150 ml) is much less than between normo- and hypovolemia (~400 ml). It should be noted that PV had decreased to the same absolute volume in the two phases by approximately 3 min of exercise (Table 3), so there was a larger decrease in PV at the beginning of exercise during the follicular phase (Figs. 3 and 4).

In three of the four experiments, the final plasma volume was not different (Figs. 1 and 3) even though there was a lower intial PV and higher T_{es} during the luteal phase. During exercise, plasma volume decreased fairly rapidly; then it was maintained at that lower volume for the rest of the exercise bout (Table 2). During passive heating the plasma volume loss was generally steadily decreasing throughout the period (Fig. 2). During the luteal phase, three of five subjects could not complete the passive heating exposure due to heat syncope. It is likely

that the low plasma volume was responsible for the dizziness and headache. These observations suggest that the lower critical level of central blood volume which must be maintained for circulatory integrity was surpassed during the passive heating experiments during the luteal phase, at least in those individuals who experienced syncope.

During the follicular phase, passive heating did not result in as great a plasma volume loss nor in such a low absolute plasma volume at the time of the last blood sample as occurred in the other three experiments. Plasma renin activity is higher at rest (15) and during exercise in the luteal phase (unpublished observations) and increased angiotensin II (Ang II) may have contributed to greater filtration as a consequence of a higher arteriolar and capillary pressure. Another partial explanation of the differing volume of fluid lost during passive heat exposure between phases of the menstrual cycle could be that there is a higher catecholamine concentration in the luteal than in the follicular phase (17). Increased catecholamine concentration would also increase arterial pressure and likely increase venous pressure as well (14,20,26), thus having the effect of increasing capillary filtration pressure as well as decreasing absorption of fluid from the postcapillary venules. Exercise could well obscure this increased net filtration during the luteal phase since there is approximately a 5 fold increase in plasma norepinephrine during exercise (5,17) indicating a much greater sympathetic nervous activity (4). The higher circulating catecholamines during exercise would result in a much greater arterial pressure and would be expected to act differentially at the various organ capillary beds to vasodilate or vasoconstrict, thus leading to the entirely different vascular volume dynamics between exercise and passive heating (13).

The observation from the present study that women hemoconcentrate less during passive heating during the follicular than the luteal phase is new and the explanation for such a phenomenon is incomplete. It has been suggested that there is a lower limit to hemoconcentration in response to passive heating or exercise, as measured by actual plasma volume reduction (13) or by reduced central venous pressure (20). Mohsenin and Gonzalez (18) have extended that hypothesis by showing increased transvascular colloid osmotic pressure and increased interstitial fluid pressure opposed unchecked fluid loss from the vasculature during maximum exercise. If the passive heat exposure during the follicular phase continued during the present investigation, the PV may have been reduced to the same volume as observed in the luteal phase, and in both phases during exercise. This plasma volume, which averaged 2.5 ℓ in these women, may be the lower limit for vascular fluid loss with adequate regulation of blood pressure.

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References

1. Allen TH, Peng MT, Chen KP, Huang TF, Chen C, Fang HS (1956) Prediction of blood volume and adiposity in man from body weight and cube of height. Metab 5: 328-345

2. Bayliss, P.H., B.A. Spruce, J. Burd (1985) Osmoregulation of vasopressin secretion during the menstrual cycle. In: Schrier, R.W. (ed) Vasopressin, Raven Press, New York pp 241-247

3. Bigland-Ritchie B, Graichen H, Woods JJ (1973) A variable-speed motorized bicycle ergometer for positive and negative work exercise. J Appl Physiol 35: 739-740

4. Christensen NJ (1979) The role of catecholamines in clinical medicine. Acta Med Scand Suppl 624:9-18

5. Christensen NJ, Galbo H (1983) Sympathetic nervous activity during exercise. Ann Rev Physiol 45:139-153

6. Drinkwater BL, Denton JE, Kupprat LC, Talag TS, Horvath SM (1976) Aerobic power as a factor in women's response to work in hot environments. J Appl Physiol 41:815-821

7. Forsling ML, Stromberg P, Akerlund M (1982) Effect of ovarian steroids on vasopressin secretion. J Endocrinol 95:147-151

8. Fortney SM, Nadel ER, Wenger CB, Bove JR (1981) Effect of blood volume on sweating rate and body fluids in exercising humans. J Appl Pnysiol 51:1594-1600

9. Fortney SM, Senay LC (1979) Effect of training and heat acclimation on exercise responses of sedentary females. J Appl Physiol 47:978-984

10. Gaebelein CJ, Senay LC (1982) Vascular volume dynamics during ergometer exercise at different menstrual phases. Eur J Appl Physiol 50:1-11

11. Gonzalez RR, Pandolf KB, Gagge AP (1974) Heat acclimation and decline in sweating during humidity transients. J Appl Physiol 36:419-425

12. Gray MJ, Strausfeld KS, Watanabe M, Sims EAH, Solomon S (1968) Aldosterone secretory rates in the normal menstrual cycle. J Clin Endocrinol 28:1269-1275

13. Harrison MH (1985) Effects of thermal stress and exercise on blood volume in humans. Physiol Rev 65:149-209

14. Henry JP, Gauer OH (1950) The influence of temperature upon venous pressure in the foot. J Clin Invest 29:855-861

15. Kaulhausen H, Leyendecker G, Benker G, Breuer H (1978) The relationship of the renin-angiotensin-aldosterone system to plasma gonadotropin, prolactin and ovarian steroid patterns during the menstrual cycle. Arch Gynakol 225:179-200

16. Keppel G (1973) Design and Analysis. Prentice Hill, Englewood Cliffs, N.J.

17. Kolka MA, Stephenson LA (1985) Thermoregulation during active and passive heating during the menstrual cycle (Abstract). Physiologist 28:368

18. Mohsenin, V., R.R. Gonzalez (1984) Tissue pressure and plasma oncotic pressure during exercise. J Appl Physiol 56:102-108

19. Nishi Y, Gagge AP (1970) Direct evaluation of convective heat transfer coefficients by naphthalene sublimation. J Appl Physiol 29:830-838

20. Rowell LB (1983) Cardiovascular adjustments to thermal stress. In: Shepherd JT, Abboud FM (ed) Handbook of physiology - the cardiovascular system III Waverly Press, Baltimore, pp 967-1023

21. Senay LC Jr (1973) Body fluids and temperature responses of heat-exposed women before and after ovulation with and without rehydration. J Physiol (London) 232: 209-219

22. Spruce, B.A., P.H. Bayliss, J. Burd, M.J. Watson (1985) Variation in osmoregulation of arginine vasopressin during the human menstrual cycle. Clin Endocrinol 22: 37-42

23. Stephenson LA, Kolka MA, Gonzalez RR (1984) Circadian and menstrual cycle variation in blood parameters (Abstract). The Physiologist 27:230.

24. Strauss MB, Davis RK, Rosenbaum JD, Rossmeisl EC (1951) Water diuresis produced during recumbency by the intravenous infusion of isotonic saline solution. J Clin Invest 30: 862-868

25. Turner C, Fortney S (1984) Plasma volume changes during the menstrual cycle (Abstract). Fed Proc 43: 718

26. Vanhoutte PM, Verbeuren TJ, Webb RC (1981) Local modulation of adrenergic neuroeffector interaction in the blood vessel wall. Physiol Rev 61: 151-247

27. Wells CL, Horvath SM (1973) Heat stress responses related to the menstrual cycle. J Appl Physiol 35: 1-5

28. Wells CL, Horvath SM (1974) Responses to exercise in a hot environment as related to the menstrual cycle. J Appl Physiol 36:299-302

29. Wilkerson, JE, Gutin B, Horvath SM (1977) Exercise-induced changes in blood, red cell, and plasma volumes in man. Med Sci Sports 9:155-158

30. Wilkerson JE, Leeds EM, Gordon GD (1985) Hematological differences in regularly cycling females with normal and low luteal progesterone (Abstract). Fed Proc 44: 846

Table 1. Individual Subject Characteristics

	Age (yr)	Height (cm)	Weight (kg)	A_D (m^2)	$\dot{V}O_2$ peak ($l \cdot min^{-1}$)	Exercise Workload (% $\dot{V}O_2$ peak)	Workload ($w \cdot m^{-2}$)
1	32	173.0	64.2	1.77	2.41	83	415
2	26	162.0	60.9	1.65	2.20	78	363
3	27	165.1	64.0	1.71	2.30	72	366
4	30	170.0	59.0	1.68	2.55	84	388
5	21	162.6	68.0	1.73	2.64	75	375
$\bar{X}$	27.2	166.5	63.2	1.71	2.42	78	381
S.D.	4.2	4.8	3.4	0.05	0.18	(6.6)	36

Table 2. Mean ($\pm$ S.D) skin temperature, esophageal temperature, change in plasma volume from pre-stress volume and oxygen consumption after every 0.2°C increase in T_{es}. An asterisk (*) indicates differences between follicular and luteal phases ($p \leq 0.05$) A dagger (†) indicates differences between passive heating and exercise in each phase.

PASSIVE HEATING:	FOLLICULAR					LUTEAL			
	$\bar{T}_{sk}$ (°C)	T_{es} (°C)	$\dot{V}O_2$ ($l \cdot min^{-1}$)	ΔPV (%)		$\bar{T}_{sk}$ (°C)	T_{es} (°C)	$\dot{V}O_2$ ($l \cdot min^{-1}$)	ΔPV (%)
Pre	-[a]	36.97 (0.23)	-	-	Pre	-	37.28* (0.22)	-	-
2	37.83 (0.45)	37.17 (0.21)	0.181 (0.02)	-1.0	2	37.96* (0.12)	37.48* (0.21)	0.198 (0.03)	-2.66
3	37.35 (0.19)	37.37 (0.23)	0.202 (0.04)	-3.14	3	37.43* (0.16)	37.67* (0.20)	0.180 (0.04)	-5.45
4	37.35 (0.33)	37.56 (0.23)	0.185 (0.01)	-5.11	4	37.75* (0.38)	37.84* (0.16)	0.231 (0.05)	-10.77
5	37.44 (0.22)	37.69 (0.19)	0.195 (0.03)	-	5	-	-	-	-

EXERCISE:	FOLLICULAR					LUTEAL			
Pre	-	36.96 (0.22)	-	-	Pre	-	37.21* (0.27)	-	-
2	37.82 (0.40)	37.17 (0.21)	1.74† (0.18)	-12.28	2	38.51* (0.38)	37.47* (0.22)	1.69† (0.09)	-7.30
3	37.73 (0.42)	37.46 (0.29)	1.93† (0.30)	-13.29	3	38.23* (0.42)	37.68* (0.23)	1.87† (0.17)	-10.73
4	37.46 (0.27)	37.65 (0.30)	1.92† (0.29)	-14.19	4	38.03* (0.39)	37.83* (0.24)	1.90† (0.09)	-13.49
5	37.32 (0.35)	37.78 (0.28)	2.02† (0.20)	-15.67	5	37.83* (0.38)	37.98* (0.25)	1.96† (0.19)	-13.30

[a] There is not sufficient data on all subjects for the mean data to be presented.

Table 3. Mean (± S.D.) blood constituents pre-stress and after each 0.2°C increase in T_{es} during passive heating . An asterisk (*) indicates differences between the follicular and luteal phases ($P \leq 0.05$) A dagger (†) indicates differences from pre-stress blood samples ($P \leq 0.05$). The symbol, psi,(ψ) indicates differences between passive heating and exercise ($P \leq 0.05$).

PASSIVE HEATING

FOLLICULAR

	Hct (%)	Hb ($g \cdot 100ml^{-1}$)	PV (ℓ)	P_p ($g \cdot 100ml^{-1}$)	TCP (g)	Na^+ ($mEq \cdot \ell^{-1}$)	K^+ ($mEq \cdot \ell^{-1}$)
Pre	36.62 (1.6)	12.30 (0.4)	2.98 (0.15)	6.96 (0.1)	207.7 (11.4)	143.0 (0.9)	4.1 (0.3)
2	36.44 (1.7)	12.46 (0.4)	2.95†ψ (0.11)	6.98 (0.2)	206.2 (11.6)	143.7 (1.2)	4.0†ψ (0.1)
3	36.92 (1.5)	12.64 (0.3)	2.89†ψ (0.11)	7.12 (0.2)	205.8 (12.9)	145.0† (1.4)	4.0†ψ (.2)
4	37.28 (1.5)	12.83 (0.4)	2.83†ψ (0.09)	7.34 (0.3)	206.0 (12.4)	146.8† (2.6)	3.9†ψ (.2)
5	-[a]	-	-	-	-	-	

LUTEAL	Hct (%)	Hb ($g \cdot 100ml^{-1}$)	PV (ℓ)	P_p ($g \cdot 100ml^{-1}$)	TCP (g)	Na^+ ($mEq \cdot \ell^{-1}$)	K^+ ($mEq \cdot \ell^{-1}$)
Pre	38.30 (1.3)	12.90 (0.4)	2.77* (0.21)	7.02 (0.2)	194.6* (13.9)	142.4 (1.5)	4.0 (0.2)
2	38.46 (1.3)	13.22 (0.4)	2.70†*ψ (0.21)	7.14 (0.2)	192.7 (15.1)	143.0 (1.2)	4.1ψ (0.3)
3	38.96 (1.5)	13.50 (0.5)	2.62*†ψ (0.22)	7.40 (0.3)	194.0 (15.5)	144.7† (1.5)	4.0ψ (0.1)
4	40.10 (1.3)	14.04 (0.3)	2.47*† (0.18)	7.80 (0.5)	193.5 (12.7)	146.4† (2.1)	4.0ψ (0.2)
5	-	-	-	-	-	-	-

a There is not sufficient data on all subjects for the mean data to be presented.

Table 4. Mean (± S.D.) blood constituents pre-stress and after each 0.2°C increase in T_{es} during exercise. An asterix (*) indicates differences between the follicular phases ($P \leq 0.05$). A dagger (†) differences from pre-stress blood sample ($P \leq 0.05$). The symbol; psi (ψ), indicates differences between passive heating and exercise ($P \leq 0.05$).

EXERCISE

FOLLICULAR

	Hct (%)	Hb ($g \cdot 100ml^{-1}$)	PV (ℓ)	P_p ($g \cdot 100ml^{-1}$)	TCP (g)	Na^+ ($mEq \cdot \ell^{-1}$)	K^+ ($mEq \cdot \ell^{-1}$)
Pre	36.48 (1.5)	12.36 (0.3)	2.97 (0.13)	6.9 (0.2)	204.7 (13.8)	142.7 (1.3)	4.1 (0.2)
2	39.06 (1.7)	13.52 (0.3)	2.60†ψ (0.11)	7.5 (0.4)	195.5 (11.6)	144.2† (3.0)	4.8†ψ (0.3)
3	39.34 (1.6)	13.62 (0.3)	2.57†ψ (0.11)	7.6 (0.3)	196.3 (11.7)	145.4† (1.7)	5.2†ψ (0.2)
4	39.52 (1.3)	13.72 (0.2)	(2.54)†ψ (0.11)	7.8 (0.3)	198.9 (12.9)	145.0† (2.5)	5.3†ψ (0.2)
5	40.16 (1.7)	13.80 (0.3)	2.50† (0.11)	7.9 (0.3)	197.2 (12.6)	--	--

LUTEAL

	Hct (%)	Hb ($g \cdot 100ml^{-1}$)	PV (ℓ)	P_p ($g \cdot 100ml^{-1}$)	TCP (g)	Na^+ ($mEq \cdot \ell^{-1}$)	K^+ ($mEq \cdot \ell^{-1}$)
Pre	37.2 (1.4)	12.6 (0.3)	2.88* (0.23)	6.9 (0.2)	198.5* (17.5)	142.8 (0.9)	4.0 (0.2)
2	39.32 (1.6)	13.32 (0.6)	2.64†ψ (0.28)	7.4 (0.4)	195.7 (18.0)	144.2† (1.2)	4.7†ψ (0.4)
3	39.78 (1.3)	13.54 (0.4)	2.62†ψ (0.18)	7.5 (0.4)	193.9 (15.5)	144.7† (1.7)	4.9†ψ (0.2)
4	40.06 (1.8)	13.92 (0.6)	2.50†ψ (0.28)	7.7 (0.3)	191.5 (16.1)	145.1† (1.3)	5.0†ψ (0.2)
5	40.04 (1.5)	13.88 (0.3)	2.50† (0.23)	7.8 (0.3)	193.6 (16.1)	--	--

Figure Legends

Fig. 1.

Mean (± S.D.) plasma volume at each esophageal temperature (mean) for both the follicular and luteal phases during passive heating. An asterick (*) indicates differences between phases ($P \leq 0.05$). A dagger (†) indicates differences from pre-stress blood samples ($P \leq 0.05$).

Fig. 2.

Mean (± S.D.) plasma volume as a function of time for both the follicular and luteal phases during passive heating. An asterick (*) indicates differences between phases ($P \leq 0.05$). A dagger (†) indicates differences from pre-stress blood samples ($P \leq 0.05$).

Fig. 3.

Mean (± S.D.) plasma volume at each esophageal temperature (mean) for both the follicular and luteal phases during exercise. An asterick (*) indicates differences between phases ($P \leq 0.05$). A dagger (†) indicates the differences from pre-stress blood samples ($P \leq 0.05$).

Fig. 4.

Mean (± S.D.) plasma volume as a function of time for both the follicular and luteal phases during exercise. An asterick (*) indicates differences between phases ($P \leq 0.05$). A dagger (†) indicates differences from pre-stress blood samples ($P \leq 0.05$).

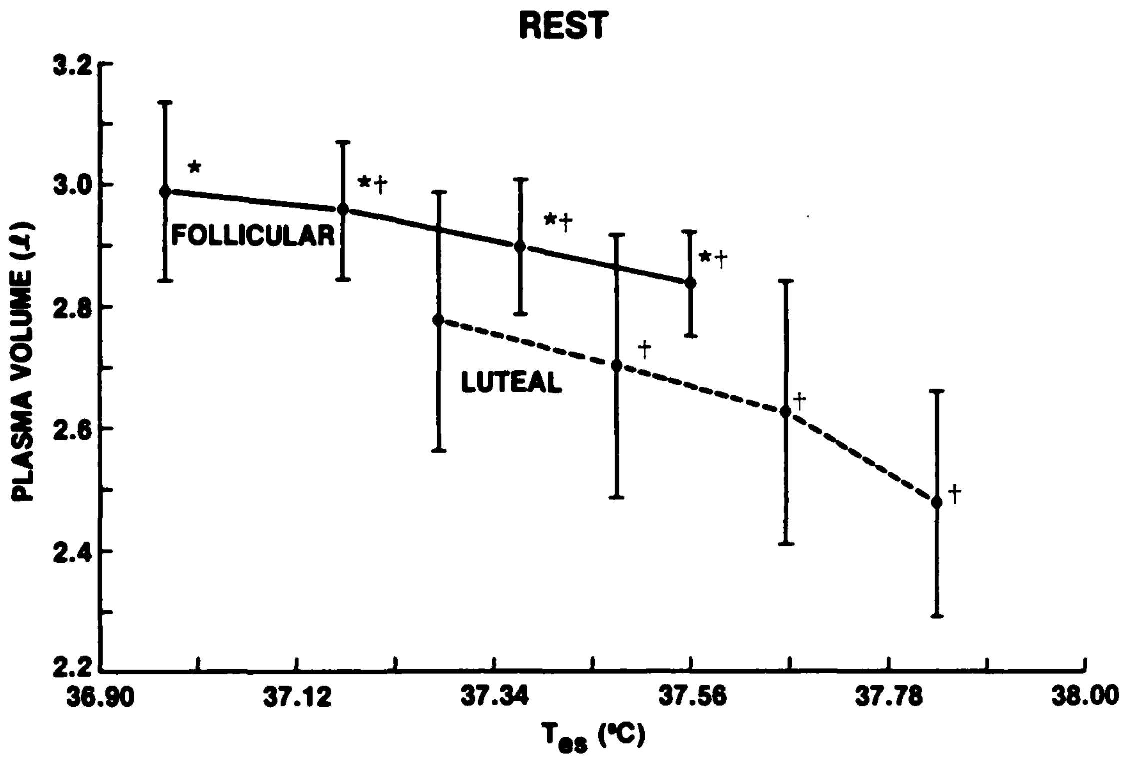

FIGURE 1

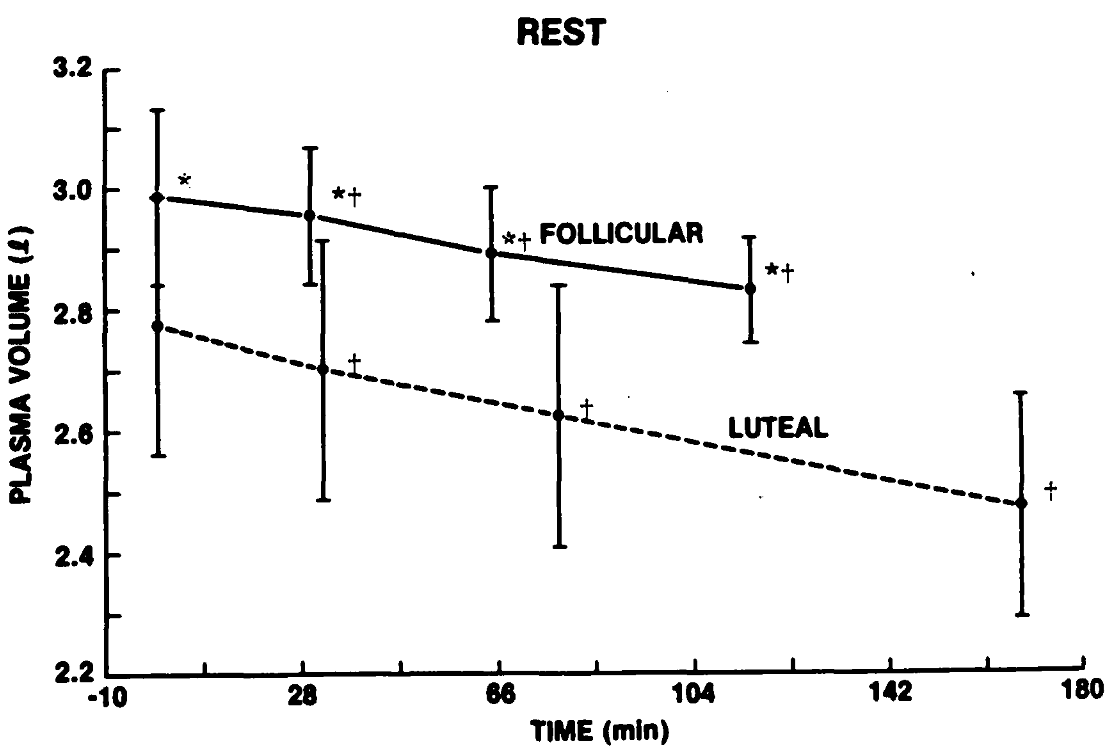

FIGURE 2

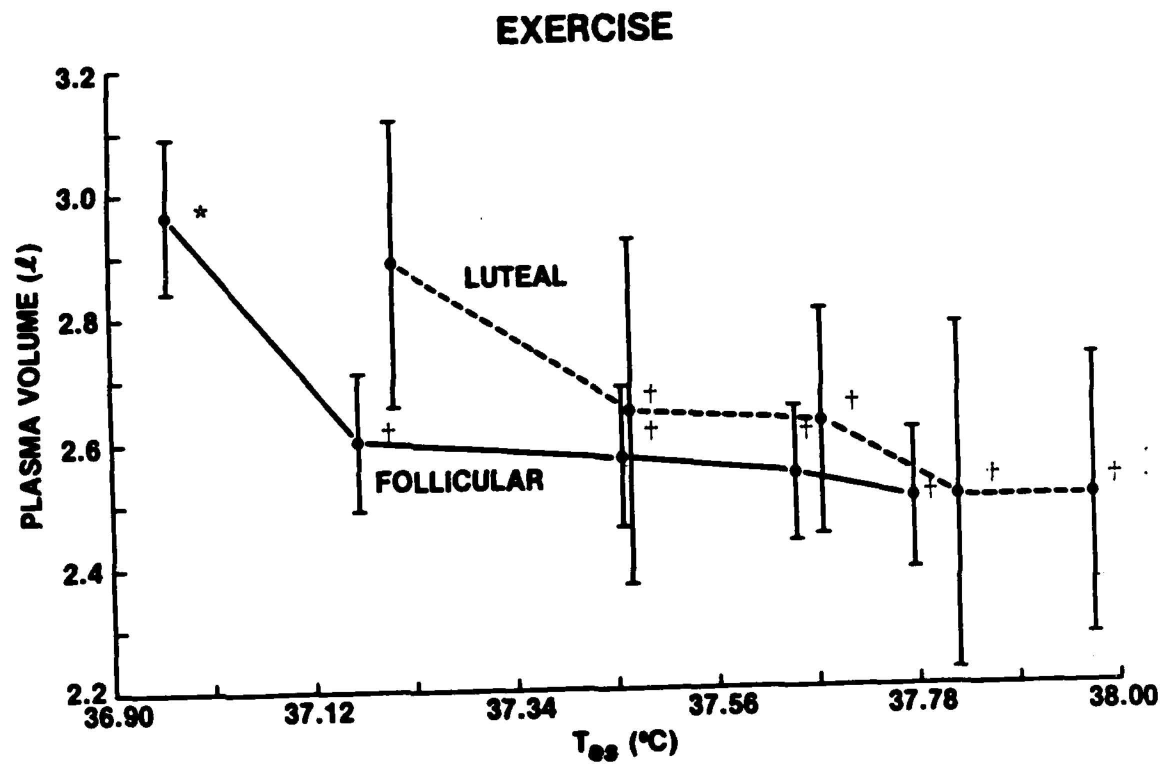

FIGURE 3

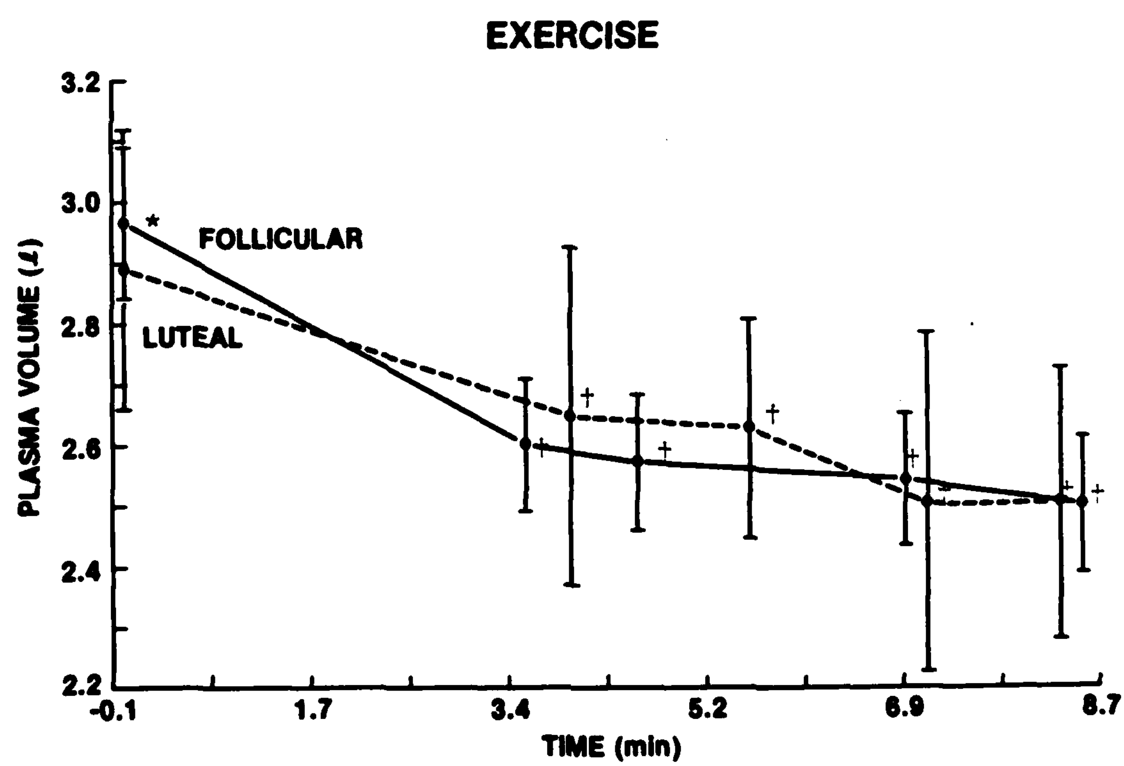

FIGURE 4

END

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